EMERGING THREATS TO TROPICAL FORESTS[1,2]

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Abstract

I highlight new and emerging threats to tropical forests, the world's most biologically diverse ecosystems. The drivers of tropical forest destruction and key perils to biodiversity have changed over the past decade and will continue to evolve in the future. Industrial drivers of forest conversion, such as logging, large-scale soy and cattle farming, oil-palm plantations, and oil and gas development, have escalated in importance, buoyed by rapid globalization, economic growth, and rising standards of living in developing nations. Biofuels are likely to grow rapidly as a driver of future forest destruction. Climate change is similarly emerging as a potentially serious driver of change in the tropics, and many species, including certain amphibians, primates, and plants, are being harmed by emerging pathogens. In general, old-growth forests are vanishing rapidly and being replaced by fragmented, secondary, and selectively logged forests, particularly in impoverished tropical countries. Road expansion continues apace and is increasingly imperiling the world's last tropical frontiers. Human population growth, especially in developing nations, remains an important underlying threat to forests. These various environmental dangers often operate in concert, magnifying their impacts and posing an even greater threat to tropical forests and their biodiversity.

Key words: Biodiversity, biofuels, China, climate change, deforestation, emerging pathogens, human population growth, industrialization, logging, overconsumption.

Tropical forests are important for many reasons—for sustaining biodiversity and indigenous cultures and for providing an array of valuable ecosystem services, such as storing carbon, limiting soil erosion, and reducing downstream flooding (Raven & Williams, 1995; Laurance, 1999; Bradshaw et al., 2007). Nearly one half of the world's tropical forests have been lost in the last few centuries and, at present, another 10 million hectares or so of native forest are being felled annually, the equivalent of roughly 40 football fields per minute (Laurance, 2010). Beyond this, many native forests are being modified, sometimes seriously, by threats such as habitat fragmentation, selective logging, overhunting, intense harvests of fuelwood and other natural products, and surface fires (Cochrane & Laurance, 2002; Peres et al., 2006; Laurance et al., 2011a).

The net effect of this constellation of changes is that many landscapes once dominated by old-growth forest are quickly becoming dominated by humans. In such landscapes, old-growth forests, if they persist at all, typically remain only in small, isolated fragments embedded within expanses of modified land, such as farms and human settlements, secondary or logged forests, and exotic-tree plantations. The future of tropical nature may well depend on the capacity of native species to persist in human-dominated landscapes and within protected areas that have become isolated and diminished as the lands surrounding them are altered by human encroachment (Laurance et al., 2012).

The proximate and ultimate (underlying) drivers of land-use change in the tropics are complex and continually evolving (Rudel et al., 2009). Understanding these drivers is important if one wishes to devise and implement effective conservation strategies. Here, I identify some emerging threats to tropical forests and their biota and briefly highlight some of their implications for nature conservation. The focus is on threats or trends that have increased markedly in the past decade or are looming just on the horizon.

Increasing Globalization and Industrialization

The ultimate drivers of deforestation are changing. In the 1980s and 1990s an expanding human populace, as manifested by hundreds of millions of small-scale farmers and rural residents living in tropical frontier regions, was often seen as the primary driver of forest loss (e.g., Myers, 1993). More recently, the situation has become more complicated. Industrial drivers of deforestation, such as large-scale agriculture, plantations, and ranching,

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[2] The author of this paper wishes to make it known to readers that the literature cited herein was up to date at the time that the manuscript was accepted for publication, in June 2013. Unfortunately, due to an extended interval between acceptance of the paper and its publication in 2015, this literature is no longer fully up to date. The author has updated two key references but not the entire paper.

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have risen sharply in importance (Butler & Laurance, 2008; Rudel et al., 2009). Other industrial activities, such as selective logging, infrastructure expansion, and oil, gas, and mineral projects, are promoting a proliferation of roads in frontier regions (Laurance & Balmford, 2013), which also promote forest loss (see below).

These trends are being driven by increasing economic globalization as well as by a rapid increase in industrialization in developing nations (Millennium Ecosystem Assessment [MEA], 2005). The rising importance of industrial drivers is provoking several important changes in the tropics. First, it appears to be accelerating the per-capita rate of forest loss in some regions (Wright & Muller-Landau, 2006). This is occurring because forests are increasingly being felled by bulldozers and other heavy equipment, rather than by small-scale landowners armed only with machetes and chainsaws. Second, it may tend to de-link the historically strong relationship between a country's population density and its remaining forest cover (Laurance, 2007a). A country like Gabon or Papua New Guinea, for instance, does not need to have a high population density to effect considerable deforestation when virtually every cut log the country produces is being rapidly exported to China (Laurance et al., 2006, 2011b).

Another important implication of increasingly industry-driven deforestation is that it affects conservation strategies. When deforestation was mostly being driven by small-scale farmers, this led to the emergence of strategies such as Integrated Conservation and Development Projects, which are designed to advance environmental conservation by promoting more sustainable rural livelihoods (e.g., Johannesen & Skonhoft, 2005). Today, however, the focus is shifting to some degree away from the myriad rural farmers to a far smaller number of large, resource-exploiting corporations (Butler & Laurance, 2008; Laurance, 2009a; Rudel et al., 2009). Many of these corporations have international stockholders and seek to export products to industrial nations where consumers tend to care about environmental sustainability. This raises the prospect for "bad corporate citizens" to be pressured by environmental activists to clean up their acts, or face the consequences of potential boycotts and a decline of their market share and corporate image.

Industrialization will surely continue to grow as scores of developing nations, such as China, India, Brazil, South Africa, and many others, continue to expand economically. The MEA projects a 300%–500% increase in global industrial activity by the year 2050 (MEA, 2005).

ROADWAY EXPANSION

We live in an era of unprecedented road and highway expansion. Many tropical regions that had been remote and largely inaccessible just one decade ago have now been penetrated by networks of roads (Laurance et al., 2009). For instance, major new highways are now criss-crossing the Amazon basin and South America (Killeen, 2007), and more than 50,000 km of new logging roads were recently detected in the Congo Basin (Laporte et al., 2007).

The problem with roads penetrating into tropical frontier regions is that their impacts often extend far beyond the road surface itself. Far too often, roads unleash a Pandora's Box of environmental problems that are difficult or impossible for governments to control. These include illegal land colonization, rampant land speculation, and influxes of illegal loggers, hunters, and miners (Laurance et al., 2009, 2014). As a result, fires and deforestation tend to increase dramatically near roads (Laurance et al., 2002; Kirby et al., 2006; Adeney et al., 2009). Such effects are especially severe and extensive around major paved highways, which provide year-round access to forest regions and tend to spawn large networks of secondary and tertiary roads and development pressure in general (Laurance et al., 2002; Kirby et al., 2006).

By dramatically increasing physical accessibility to forests, road expansion is one of the most important factors determining the magnitude and rate of forest destruction. For instance, road expansion is projected to have far-reaching effects on the future patterns of forest disruption in the Amazon (Fig. 1) (Laurance et al., 2001; Soares-Filho et al., 2006). It is also important to emphasize that road expansion is an activity that is highly amenable to policy modification (Laurance & Balmford, 2013). For instance, carbon-offset funds might be used to promote the rerouting or closure of frontier roads in vulnerable regions in order to reduce deforestation and atmospheric carbon emissions. A list of the world's most environmentally destructive tropical roads was provided in Laurance et al. (2009).

CHINA'S ROLE IN ILLEGAL LOGGING

In the tropics, one of the most profound changes in the last decade is the stunning rise of timber consumption by China, which has completely transformed tropical timber markets. China is now overwhelmingly the biggest global consumer of tropical timber, importing around 40 to 45 million m^3 of timber annually (Laurance, 2008a). In layman's terms, this means that more than one half of all

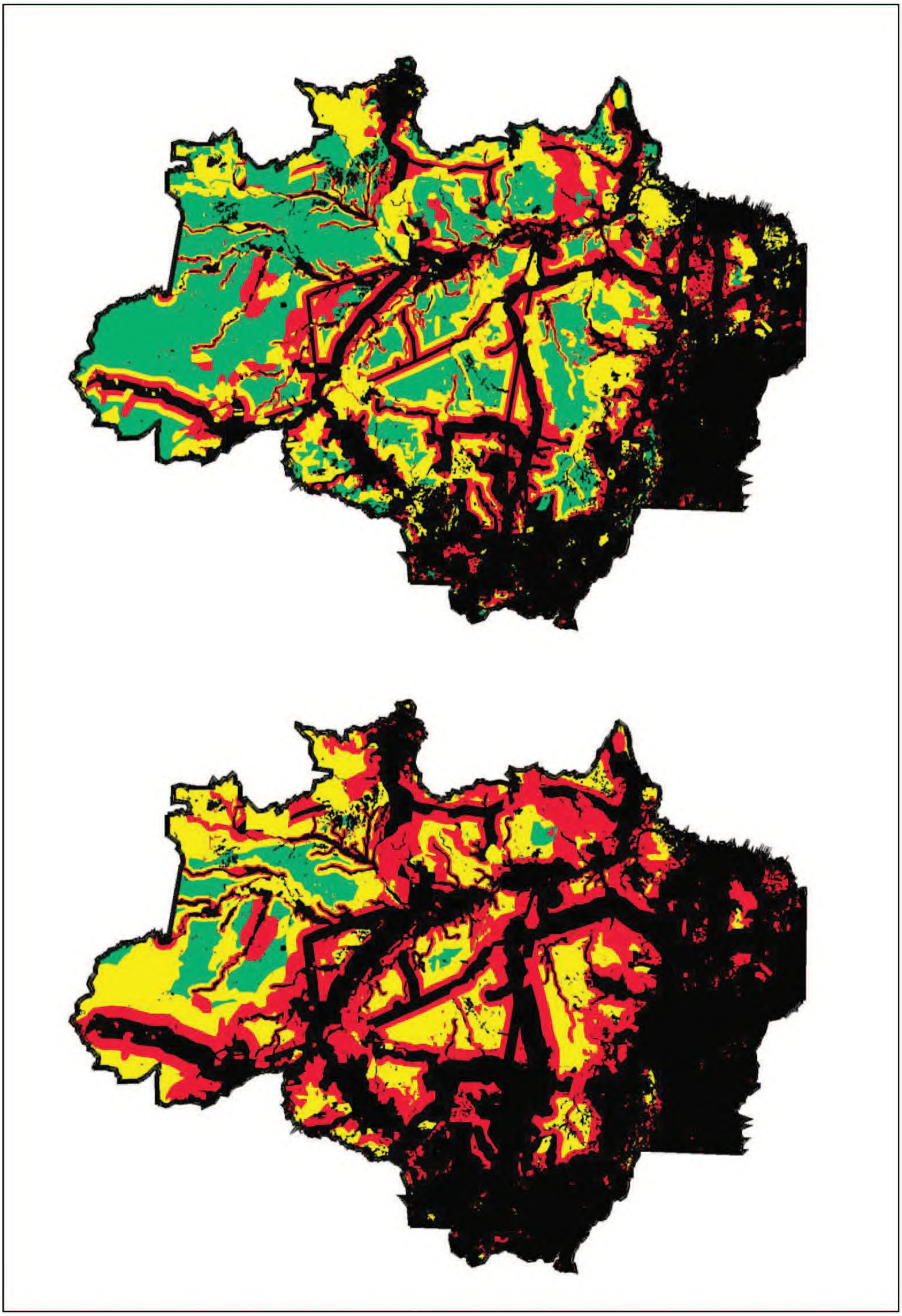

Figure 1. Roads are projected to have a major impact on future patterns of forest loss, fragmentation, and degradation in the Brazilian Amazon, which contains about 40% of the world's remaining tropical rainforest (~3.35 million km^2). Shown are "optimistic" (above) and "non-optimistic" (below) scenarios for the region in the year 2020 (black is deforested or heavily degraded, including savannas and other nonforested areas; red is moderately degraded; yellow is lightly degraded; and green is pristine) (adapted from Laurance et al., 2001). The Brazilian Legal Amazon region includes the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, and much of Mato Grosso and Maranhão.

timber being shipped anywhere in the world today is destined for China—a staggering figure! Indeed, many nations in the Asia-Pacific region and Africa now export the bulk of their timber to China (Globaltimber, 2011).

China faces three main criticisms over its role as the globally dominant timber consumer (Laurance, 2008a). First, the country has been remarkably aggressive in pursuing timber supplies globally, and in this capacity has funded or supported major new road and transportation projects to open up remote regions to exploitation, while being little preoccupied with other concerns such as social or environmental equity. Second, China has almost exclusively sought raw timber (round-logs), which is the least economically beneficial way for developing nations to exploit their timber resources. Round-logs provide only limited royalties and relatively little employment, workforce training, value-adding, or industrial development for timber-producing nations, with most of the profits being realized by foreign loggers and shippers and by wood-products manufacturers in China.

Finally, China has been a poor global citizen in attempting to combat the scourge of illegal logging (Stark & Cheung, 2006; Laurance, 2008a), which is a serious problem in many tropical nations. In some countries, one half or more of all timber entering commercial markets is effectively stolen, with no payment of government royalties and no environmental controls over cutting operations. Illegal logging is slowly diminishing globally, but this is despite, rather than because of, China's influence (Lawson & MacFaul, 2010). For this reason China is becoming increasingly vulnerable to a major boycott of its wood products, two thirds of which are exported internationally (Laurance, 2007b).

EXPANSION OF BIOFUELS

Global energy demands are rising in concert with growing industrialization and living standards and an expanding human populace. A key concern is the finite nature of most high-energy-density liquid fuels, particularly petroleum and its derivatives, which power virtually the entire global transportation sector and also provide some electricity generation. At present, around 85 million barrels of petroleum are consumed each day, and many observers believe we are approaching or have reached "peak oil," the point at which available petroleum supplies inevitably begin to decline (Roberts, 2005).

With the economically realistic technologies available at present, biofuels represent the most likely alternative to petroleum. The pressure to rapidly scale up biofuel production will surely intensify as petroleum prices increase in the coming decades (and note that, because of the nonlinear nature of supply–demand curves and relative inelasticity of petroleum demand, a 5% surge in demand or a 5% decline in supply will lead to far more than a 5% increase in petroleum prices).

The expansion of biofuel production will likely be concentrated in the tropics. The tropics is where plants, which are the main feedstocks for biofuels, grow the fastest. It is also where land is typically the cheapest, certainly more so than in productive temperate regions. At least 35 million hectares of land (an area the size of Germany) is likely to be devoted to biofuel production by the year 2030, and most expansion will be in tropical countries (Sunderlin et al., 2008).

The proliferation of tropical biofuels is likely to have two negative impacts on environmental conservation (Laurance, 2008b). First, it will promote the large-scale conversion of forests and other native ecosystems for biofuel or food production to help offset the expansion of biofuel crops onto current food-producing lands. Second, by driving up competition for land and thereby elevating land prices, it will increase opportunity costs for conservation. Under such circumstances, carbon-trading will become less viable as a means to reduce deforestation and is likely to be competitive only for areas that are remote or that have poor, unproductive soils. Such areas, by virtue of their remoteness and low agricultural productivity, are the least threatened by forest conversion.

It is important to emphasize that biofuels can promote deforestation both directly and indirectly (Scharlemann & Laurance, 2008). Where they do so directly, such as when a forest is felled to produce sugarcane for bioethanol, it is obvious that that biofuel in question is poor from an environmental perspective and should, therefore, be avoided. This is because, in addition to its impacts on biodiversity and other ecosystem services, long intervals of biofuel production ranging from decades to centuries would be needed to "pay back" the atmospheric carbon emissions created by destroying the forest initially (Gibbs et al., 2008). Far more insidious, however, is that biofuels can promote deforestation in cryptic ways. For instance, generous corn subsidies in the United States designed to promote domestic biofuel production may well have promoted Amazon deforestation. This occurred when many U.S. farmers switched from producing soy to corn, causing a spike in global soy prices and a subsequent increase in deforestation in soy-producing states in the Amazon (Laurance, 2007c).

HUMAN POPULATION GROWTH

The United Nations projects that by the end of this century, the Earth will have between 9.6 and 12.3 billion people, with population growth continuing even further beyond this (Gerland et al., 2014). The human populace reached the seven billion mark in 2011 (Engelman, 2011). In the coming decades, most of the additional three billion people will be added to the rosters of tropical nations. The only major exceptions are the Middle East and northern Africa, where high population growth will be attributable to a strong Muslim influence, and the United States, where high immigration, mostly from Latin America, is expected to be a major contributor (Population Action International [PAI], 2006).

In a fundamental sense, population growth is one of the most pervasive drivers of deforestation and environmental degradation. In our highly interconnected world, population pressures manifest themselves both locally and globally; for instance, growing international demand for wood products, paper pulp, and foodstuffs are helping to spur deforestation across much of the tropics. Furthermore, population densities and growth rates both tend to be very high in biodiversity hotspots (Cincotta et al., 2000), which contain large concentrations of species that are both locally endemic and imperiled by extinction. Among nations that contain biodiversity hotspots, population growth rates are a strong and positive predictor of deforestation rates (Jha & Bawa, 2006). Similarly, nations that have high population densities tend to have many endangered bird and mammal species (McKee et al., 2003).

With some notable exceptions (e.g., Ehrlich et al., 1997; Engelman, 2011), population issues are rarely highlighted in public discourses about environmental crises, migration issues, and domestic and international conflict. This happens in part because these issues are excruciatingly sensitive. For instance, my colleagues and I were recently labeled as "misanthropic" by a pro-logging lobby group, World Growth International. This was in response to our suggestion that Papua New Guinea, where rapid population growth is promoting both social instability and environmental degradation, should improve family planning and educational support for young women (Laurance et al., 2011b).

EMERGING PATHOGENS

We live in an era of astonishing international mobility, one in which people and their associated goods and species are in a constant state of flux. Microbes are also being moved at an exceptional pace, as evidenced by the fact that a novel human flu virus such as H1N1 can appear suddenly in southern Mexico and, in just months, have spread globally. Natural ecosystems are also being bombarded by potential new pathogens, and the resulting "pathogen pollution" could be a far more serious threat to biodiversity than many appreciate (Cunningham et al., 2003).

Novel pathogens can arise in ecosystems by a variety of means, such as host-switching, gene-swapping with other microbes, and especially by moving into a new geographic region where they encounter an abundance of unexposed, immunologically naive hosts (Daszak et al., 2000). Some of the most dramatic animal and plant mortality events ever witnessed were caused by exotic pathogens or new disease vectors. Past examples include the mass die-off of African ungulates from rinderpest (Plowright, 1982), the global extinctions or widespread extirpations of endemic Hawaiian birds from avian malaria (Atkinson et al., 1995), and the near extirpation of *Diadema* sea urchins in the Caribbean Sea (Lessios et al., 1984). Today, in addition to taking a severe human toll in Equatorial Africa, Ebola hemorrhagic fever is burning its way across the Congo Basin, causing mass mortality of gorillas and chimpanzees (Walsh et al., 2003; Thompson, 2014), whereas white-nose disease (a fungal pathogen) has killed millions of bats in North America (Blehert et al., 2009). Although little attention has focused on emerging pathogens of plants in native forests, fungal diseases caused by exotic *Phytophthora* species are known to cause severe, localized mortality of rainforest plants globally (Uchida & Aragaki, 1991; Anderson et al., 2004).

Perhaps the most devastating of all emerging wildlife pathogens is the chytrid fungus currently driving global amphibian declines (Laurance et al., 1996; Berger et al., 1998; Skerratt et al., 2007). Around 200 frog species, mostly from tropical and subtropical regions, have been driven to global extinction or been severely reduced in numbers by the fungus (Skerratt et al., 2007). Some have argued that the chytrid is merely an opportunistic pathogen attacking amphibians weakened by some unknown environmental stressor. However, a range of genetic, immunological, and other evidence suggests far more strongly that the chytrid is an emerging pathogen of exceptional virulence (Skerratt et al., 2007; Laurance, 2008c). It has been hypothesized that the chytrid fungus originated in Africa (Weldon et al., 2004), though it is now spreading rapidly throughout the world, even into some of the most pristine ecosystems on earth.

The chytrid fungus and other well-documented emerging wildlife pathogens may be merely the tip of the iceberg. In general, we tend to have a good understanding of pathogens that affect humans and our domestic animals and important food crops. Beyond this, knowledge trails off dramatically. As molecular genetics and other techniques to detect foreign pathogens improve, we may discover that emerging diseases, largely driven by the unprecedented mobility of contemporary humanity, are one of the most serious and pervasive threats to biodiversity. On top of this, the latitudinal and elevational limits of many microbes are likely to expand under global warming (Epstein, 2001; Harvell et al., 2002), and this will further increase the impacts of foreign pathogens.

CLIMATE CHANGE

It goes beyond the scope of this paper to delve in much detail into climatic and atmospheric changes, but I would like to highlight two issues of particular relevance for the tropics. The first is the potentially serious impact of global warming on higher-elevation tropical species. When people think of species vulnerable to global warming, visions of high-latitude species such as polar bears and caribou tend to spring to mind. However, tropical species are often more thermally specialized (e.g., Janzen, 1967; Deutsch et al., 2008; Wright et al., 2009). A polar bear, for instance, has to tolerate huge swings in temperature during the course of the year, from frigid winters to relatively balmy summers. But in the tropics, the conditions are far more stable, allowing thermal specialists to evolve and persist. Indeed, the main axis of thermal variation in the tropics relates to elevation; on average, temperatures drop by 6°C for every 1000 m rise in elevation. For this reason, many tropical species tend to be elevational specialists, either restricted to the lowlands, to mid-elevations, or to higher elevations (Janzen, 1967; Huey, 1976; Laurance et al., 2011c). Species limited to higher elevations are geographically isolated from their high-elevation brethren, frequently allowing them to evolve into locally endemic species (Fjeldså & Lovett, 1997). If one examines maps of the global distribution of endemic species, using warmer colors for areas with many local endemics and cooler colors for areas with few endemics, the world's tropical mountains seem to be on fire.

In addition to harboring a rich, highly endemic biota, tropical mountains appear highly vulnerable to global warming. Global warming could shrink and fragment the geographic range of species adapted to cool, wet montane conditions, increasing the likelihood of extinction (Williams et al., 2003; Thomas et al., 2004). Warming will also tend to elevate the cloud base on tropical mountains, reducing moisture inputs and increasing thermal radiation and desiccation stress (Pounds et al., 1999). Species in montane habitats may also have to contend with the arrival of lower-elevation competitors, predators, and pathogens as climates warm (Epstein, 2001; Harvell et al., 2002).

Modeling studies of endemic montane vertebrates in tropical Queensland suggest that a mean temperature rise of just 2°C will be enough to drive perhaps one eighth of all species to extinction (Fig. 2). If temperatures rise by more than 6°C, the models suggest, virtually all of the montane endemics are likely to vanish (Williams et al., 2003). As illustrated by the near-extinction of the northern population of the lemuroid possum (*Hemibelideus lemuroides*), which is confined to cool montane forests above 1100 m elevation in north Queensland, brief but intense heat waves, rather than steadily rising temperatures, might be the death-knell for many tropical species (Laurance, 2009b, 2011).

Another big concern is our alarmingly weak ability to predict future climate change in the tropics. We know that conditions will generally warm but, beyond this, our capacity to project future changes for any specific locality is often exceedingly poor. This point is illustrated by a series of global circulation models (GCMs) in Figure 3, each devised by leading research teams, for South America (Vera et al., 2006). GCMs are probably our most powerful tool for projecting future climate change, and these models show a series of scenarios for projected greenhouse gas concentrations for the latter part of this century. Each model in Figure 3 was run under identical conditions, and yet they vary hugely. Some, for instance, project that the Amazon basin will only become slightly warmer, whereas others suggest temperatures in the region will rise dramatically (Vera et al., 2006). And if projections of future temperatures seem wildly variable, projected precipitation is even worse. Some of the GCMs in Figure 3 suggest the Amazon basin will become wetter in the future, whereas others are far drier. Collectively, what these models illustrate is our often appalling poor capacity to downscale from GCMs, to make local-scale projections about future tropical climates (Laurance & Useche, 2009). This is especially the case for precipitation, which is vital for the persistence of tropical ecosystems. In particular, even relatively small declines in rainfall during the dry season, when forests are most drought-stressed and vulnerable to fire, could be potentially devastating for forests (Cochrane & Laurance, 2008).

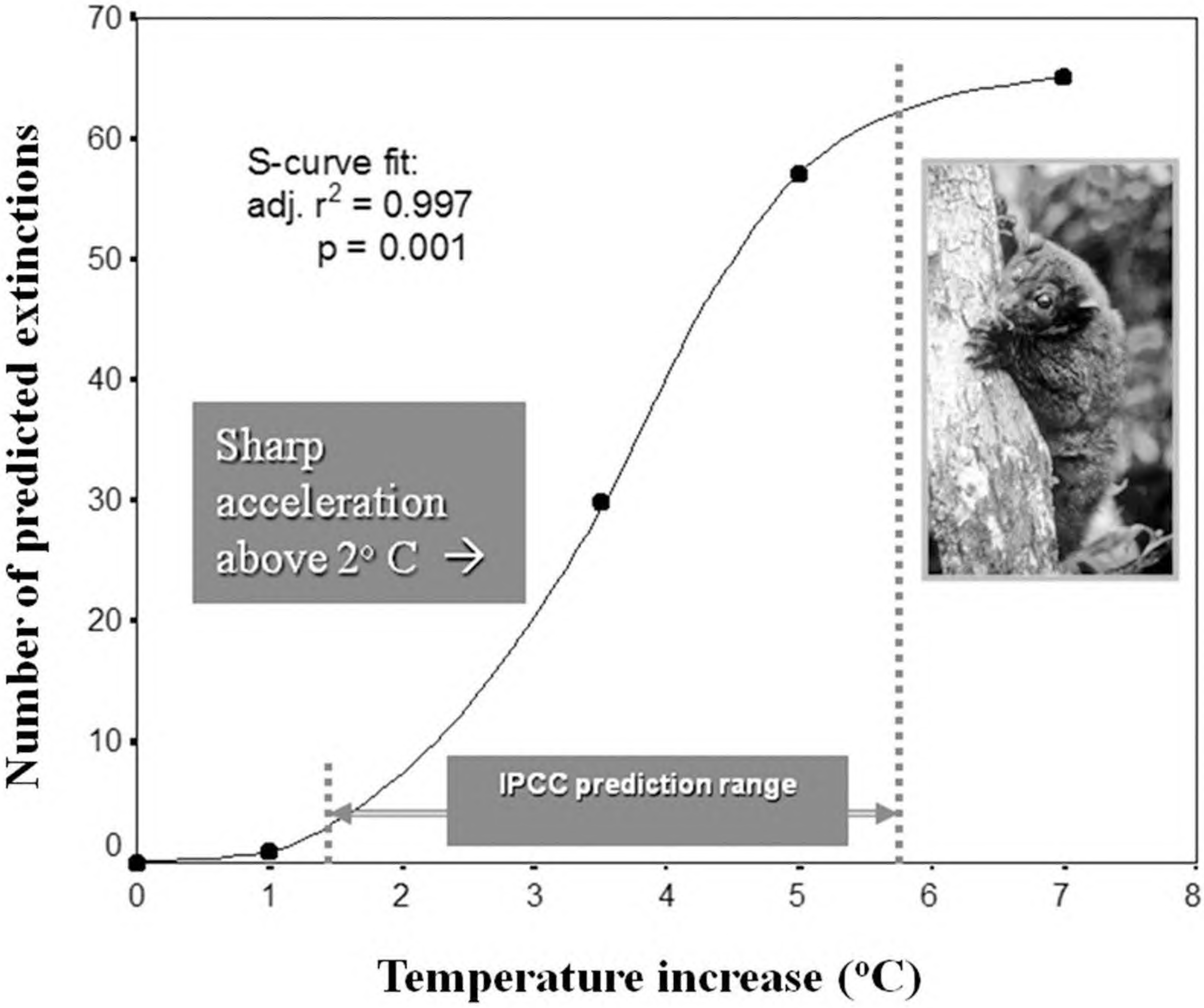

Figure 2. Projected increase in extinctions of 65 upland-endemic vertebrates in the tropical rainforests of northern Queensland as a function of future global warming (image reproduced, with permission, from S. E. Williams). Inset: a lemuroid ringtail possum (*Hemibelideus lemuroides*), which is restricted to cool, montane rainforests (photo by W. F. Laurance).

ENVIRONMENTAL SYNERGISMS

When speaking in public, I sometimes challenge my audiences to identify any part of the planet that is experiencing just a single environmental change. They invariably fail because no such place exists. The world is experiencing a bevy of environmental changes, from climatic change and habitat disruption to pollution and the loss of countless species, all at once. To use the analogy of a boxing match, we are not just hitting nature with an occasional jab, but with a flurry of punches landing all at once.

Such combinations of environmental threats could be the downfall for many imperiled species. For instance, an analysis of endangered and extinct mammal, bird, and amphibian species using data from the IUCN Red Data Book suggests there are far more species than expected by chance alone that are being imperiled by combinations of environmental threats, rather than by a single threat (Laurance & Useche, 2009). The tiger (*Panthera tigris*), for example, is not merely being endangered by destruction of its habitats or by widespread persecution and hunting. Rather, it is the combination of these environmental insults operating in concert that is the biggest threat to its survival. Many other synergisms—between logging and hunting (Wilkie et al., 1992), habitat fragmentation and fire (Cochrane & Laurance, 2002), and habitat disruption and climatic change (Thomas et al., 2004; Thuiller et al., 2006)—are likely to have serious impacts on tropical biodiversity.

CONCLUDING THOUGHTS

I have focused here on identifying a number of emerging or potential threats to tropical forests and their biodiversity, but it is important to emphasize that "it is not all bad news." There are, in fact, many positive developments in tropical nature conservation that one could highlight. Protected areas have increased substantially in recent decades and now encompass 14.8% of the global land area (although only 5.8% is in strictly protected areas [IUCN

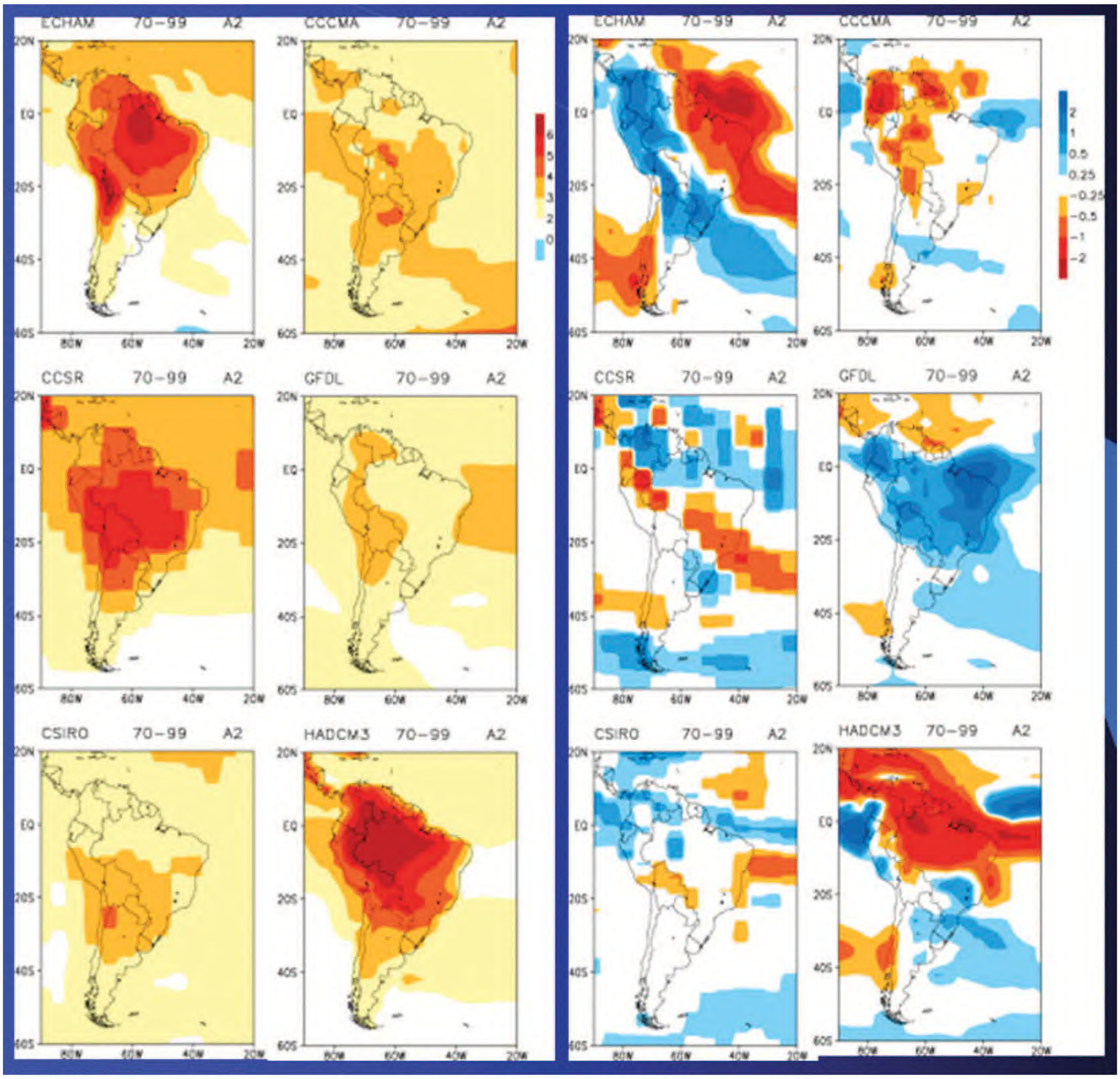

Figure 3. A variety of different global circulation models (GCMs) used to project changes in temperature (left) and precipitation (right) for South America, for the latter part of this century. All models were run under the same hypothetical conditions, using the high greenhouse-gas scenario of the Intergovernmental Panel on Climate Change (image adapted from IPCC, 2001). The vertical and horizontal axes on each model show latitude and longitude, respectively.

categories I–IV]; Jenkins & Joppa, 2009). Public awareness of the importance of tropical forests is clearly increasing (Baranzini et al., 2009), as is the number of nongovernmental groups focusing on environmental issues and indigenous peoples (Clark, 1995). International carbon-trading has emerged as a mechanism to slow tropical deforestation while simultaneously reducing greenhouse-gas emissions (Laurance, 2007d; Venter et al., 2009). While many challenges remain, conservation actions are having a positive impact on biodiversity protection at many levels (Brooks et al., 2009; Sodhi et al., 2011; Laurance, 2013).

Rather than viewing the tropics as a lost cause, one should instead view this as a time of great opportunity for tropical conservationists. Having a better understanding of the key threats to tropical ecosystems should help to guide and focus our conservation efforts and increase their effectiveness.

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